ECE 595

M03-LONG TERM EVOLUTION TECHNOLOGIES

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4G LTE

- 3G performance is no longer sufficient to meet needs of high-performance multi-media, full-motion video and wireless teleconferencing applications.

- High data rate demand.

- 3G is based on primarily a wide-area concept. Hybrid networks that utilization both wireless LAN (hot sport) concept and cell or base-station wide area network design is required.

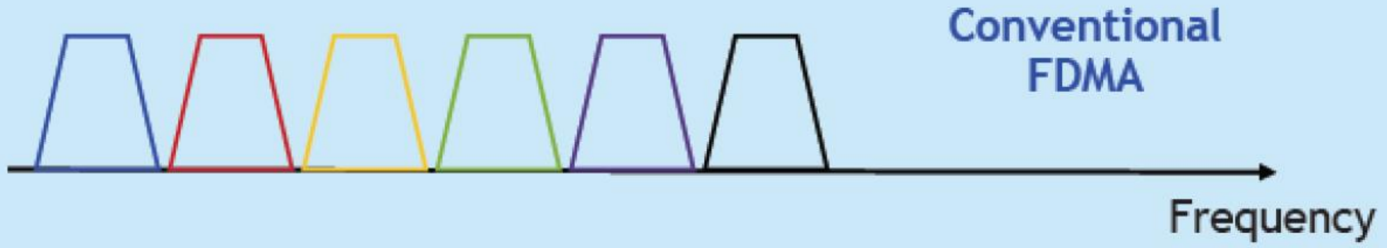
- Demand for wider bandwidth.

- More efficient modulation schemes that cannot be retrofitted in to 3G infrastructure are now available. Hence the need for a new generation technology.

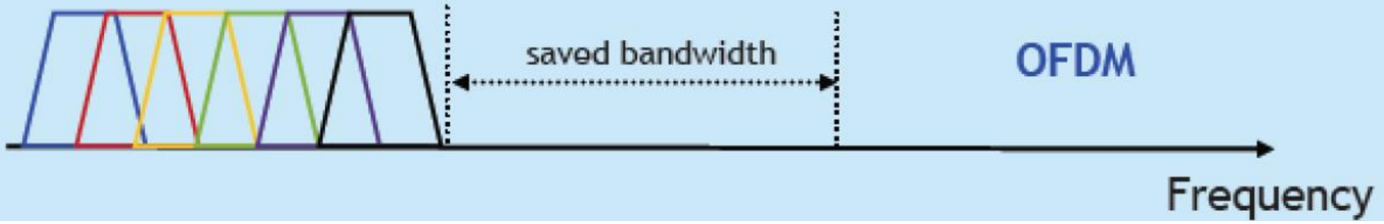
❑ Multicarrier Technology

➢ Orthogonal Frequency-Division Multiplexing (OFDM)

- FDM is nothing new: carriers are separated sufficiently in frequency so that there is minimal overlap to prevent cross-talk

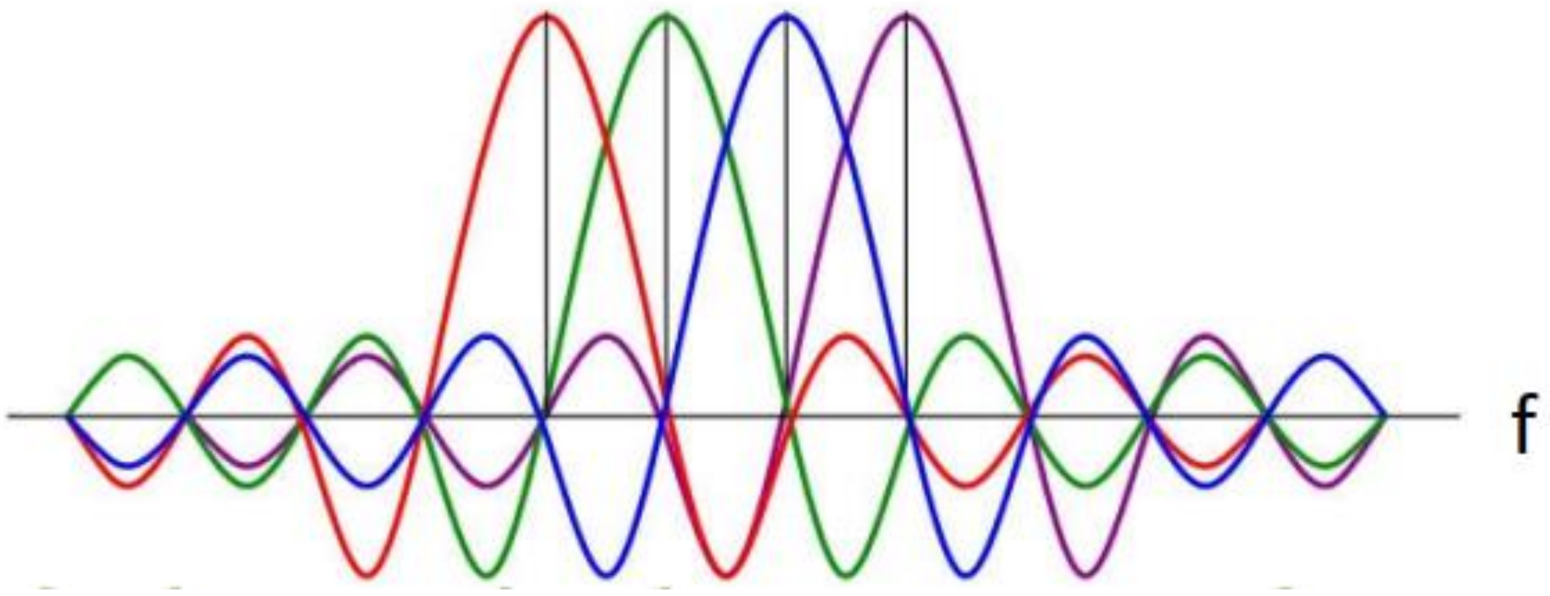


- OFDM: still FDM, but carriers can actually be orthogonal (no cross-talk) while actually overlapping, if specially designed → saved bandwidth!



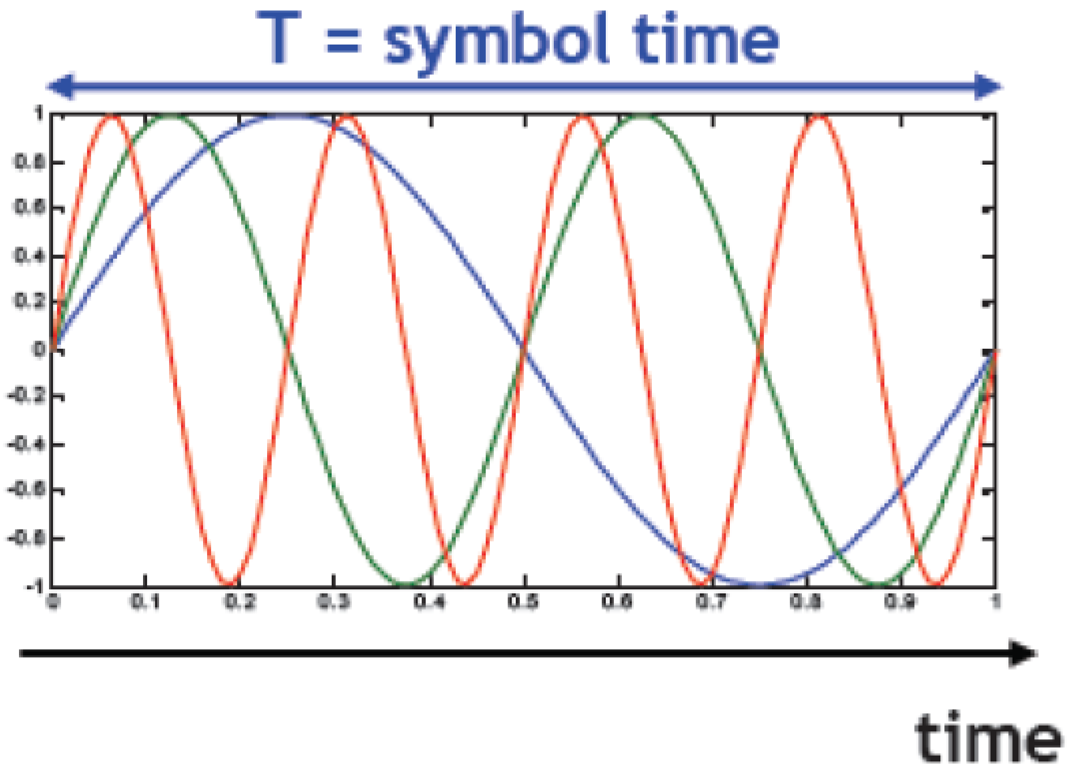
❑ Multicarrier Technology

- This is what the overlapping carriers actually look like in the frequency domain.
  - ✓ The peak a subcarrier is lined up with the nulls of the other subcarriers.



❑ Multicarrier Technology

- ➢ In time domain, an OFDM signal is the weighted summation of sinusoid signals with different carrier frequencies.
  - ✓ Each sinusoid has an integer number of cycles over the symbol time.

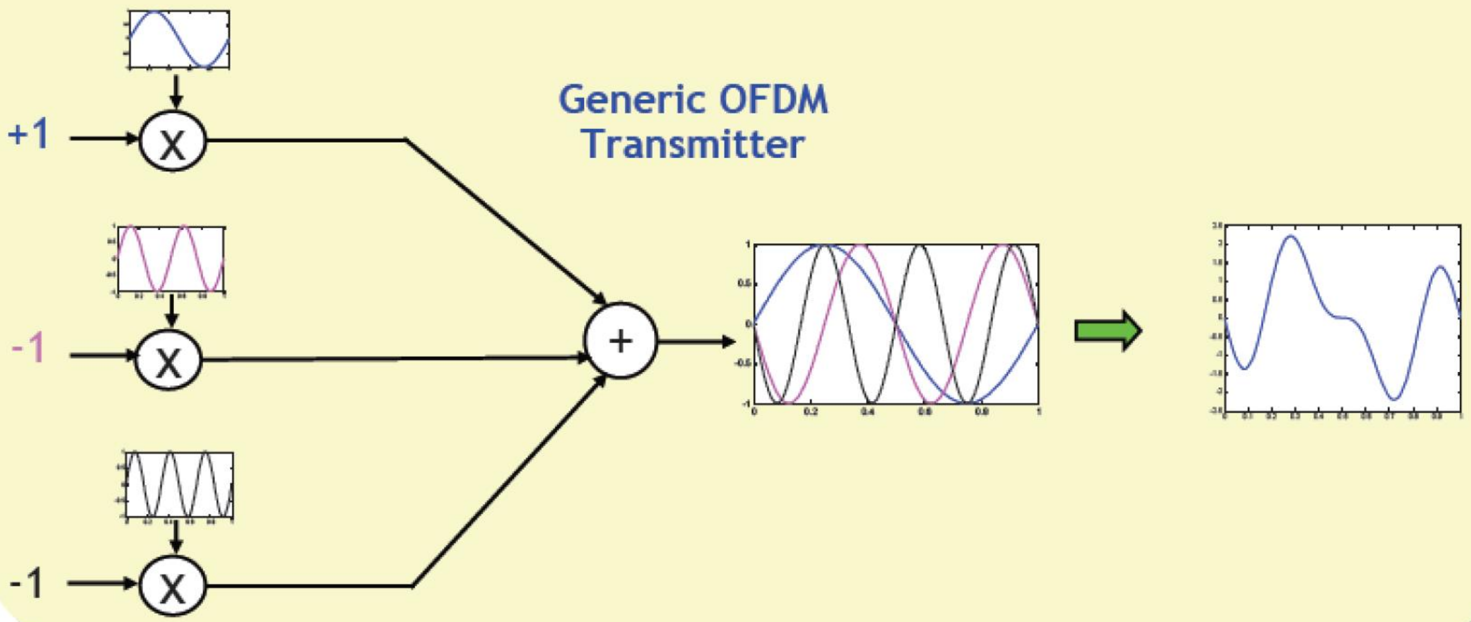


❑ Multicarrier Technology

➢ Orthogonal Frequency-Division Multiplexing (OFDM)

- Because the subcarriers are orthogonal, we can send several symbols in parallel using different subcarriers, and they will not interfere with each other

Example: BPSK symbols +1, -1, -1

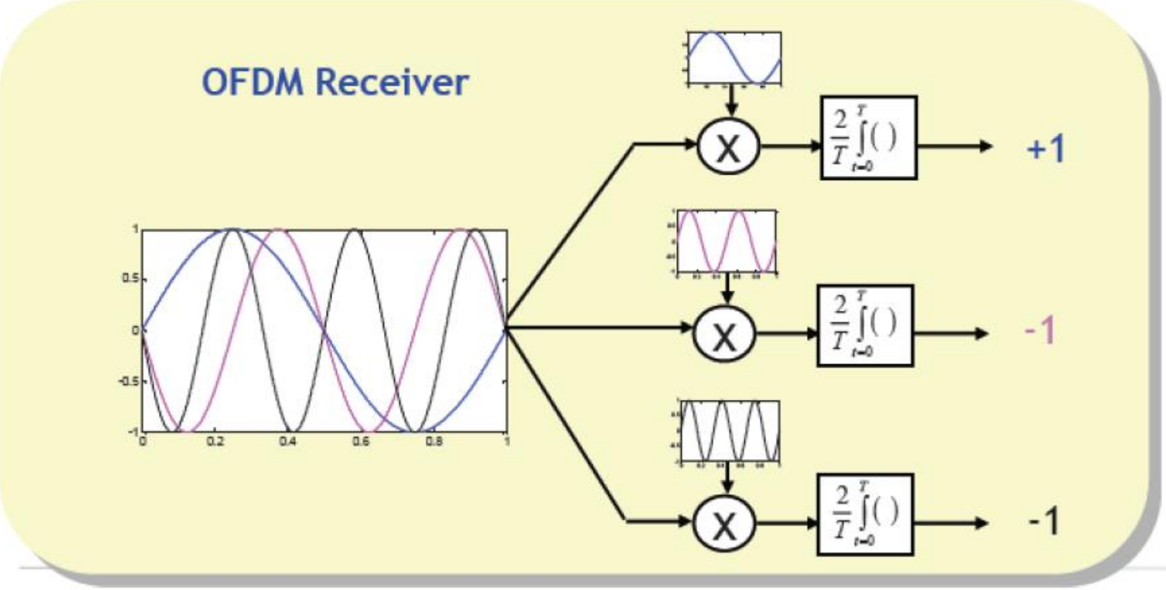


❑ Multicarrier Technology

➢ Orthogonal Frequency-Division Multiplexing (OFDM)

- Extracting the individual symbols relies on the orthogonality property of the set of sine waves we are using over the symbol period T

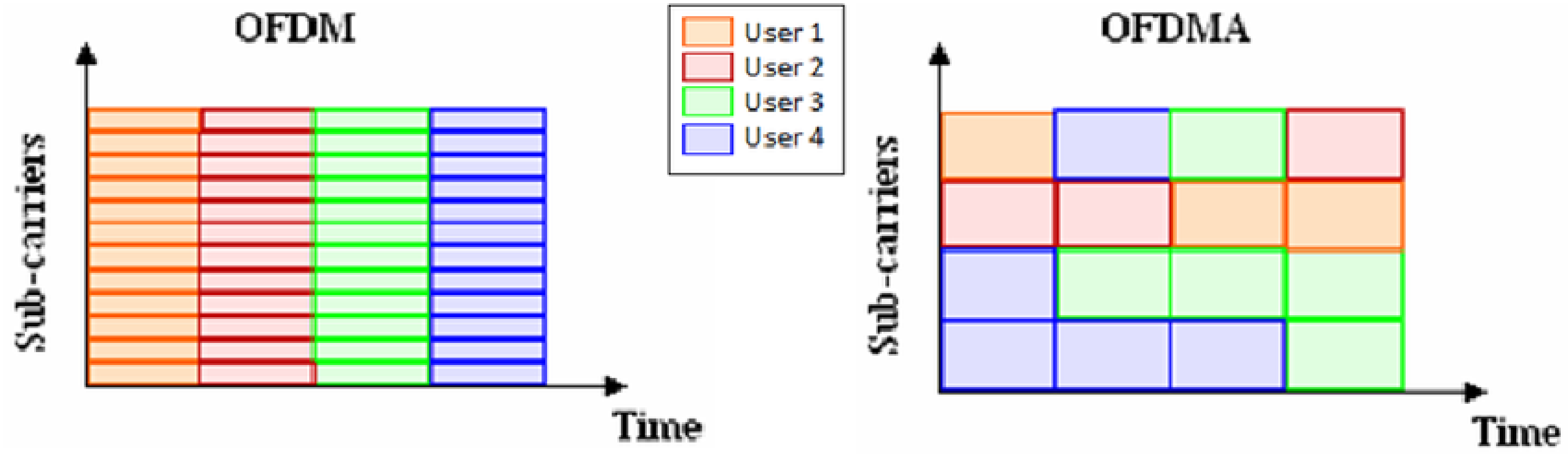
$$\int_{t=0}^{T} \sin\left(\frac{2\pi m t}{T}\right)\sin\left(\frac{2\pi n t}{T}\right)dt = 0 \quad for\ m \neq n$$



❑ Multicarrier Technology

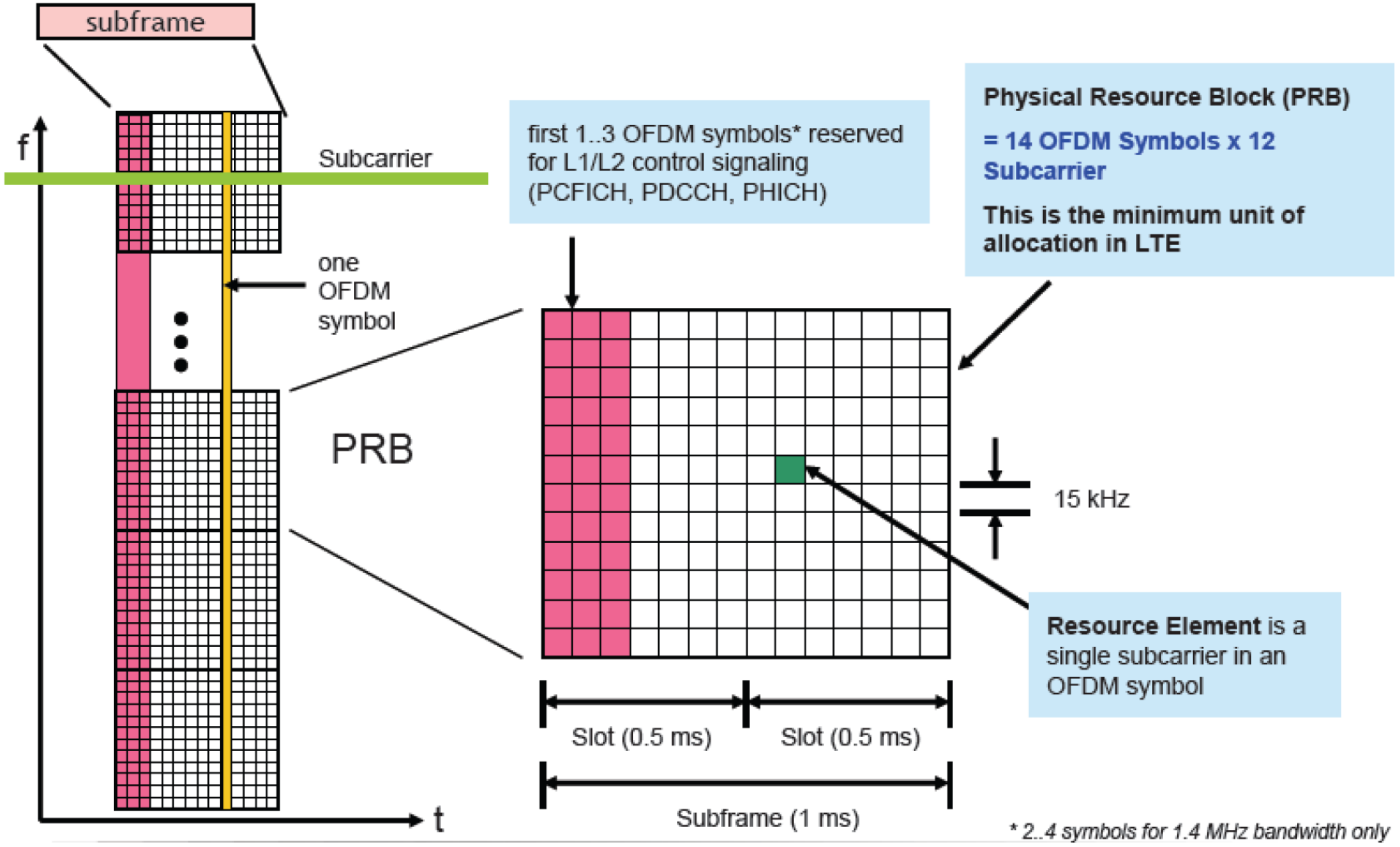
➢ From OFDM to OFDMA (Orthogonal Frequency-Division Multiple Access)

- ✓ Both apply TDM + FDM
- ✓ In OFDM, all sub-carriers of the symbol are used for carrying data to a specific user.
- ✓ In OFDMA, different sub-carriers may carry data from different users.



- ✓ OFDMA's dynamic allocation enables better use of the channel.
- ✓ OFDMA is used as the access technology in downlink communications (from BSs to UEs)

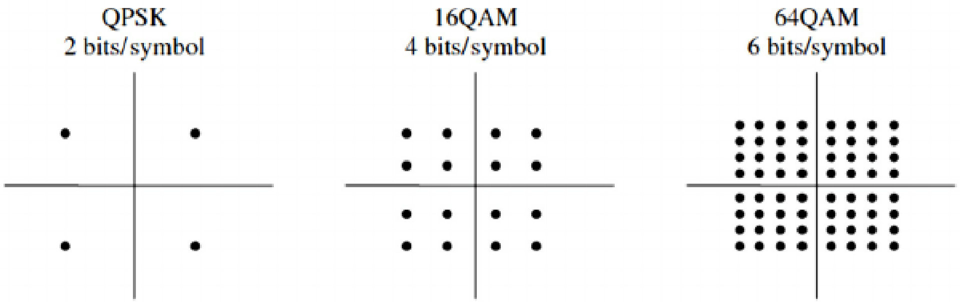
❑ Physical channel design of OFDMA



PCFICH = Physical Control Format Indicator Channel, **PDCCH** = Physical Downlink Control Channel, **PHICH** = Physical HARQ Indicator Channel

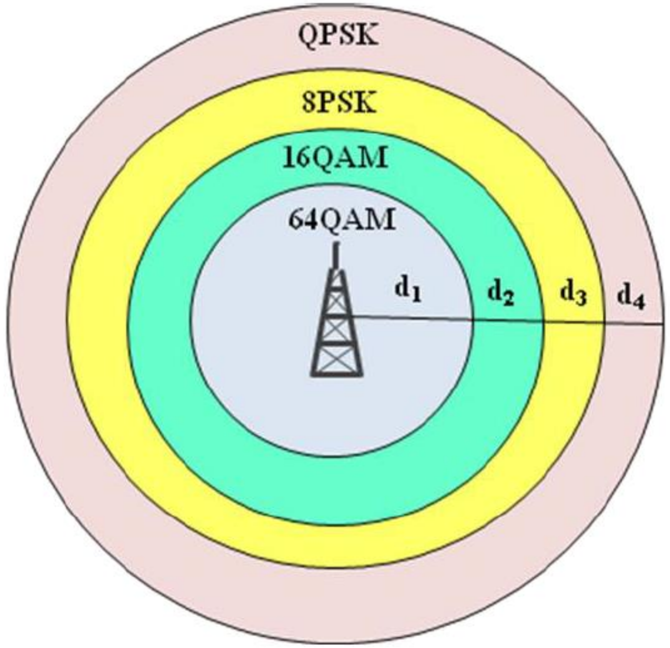
❑ Physical channel design of OFDM

- Adaptive modulation
  - In high SINR, higher-order modulation schemes will be used (e.g., 64 QAM).
    - Higher-order modulation scheme → one resource element can carry more bits.



  - In low SINR, low-order modulation schemes will be used (e.g., QPSK).

- Question: What are the maximum bits that a PRB could carry?

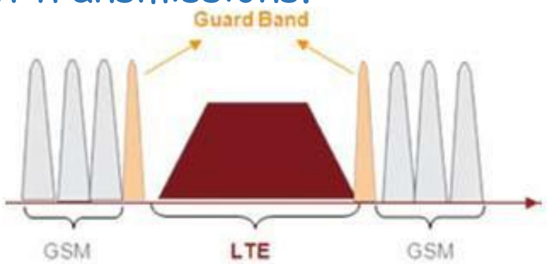


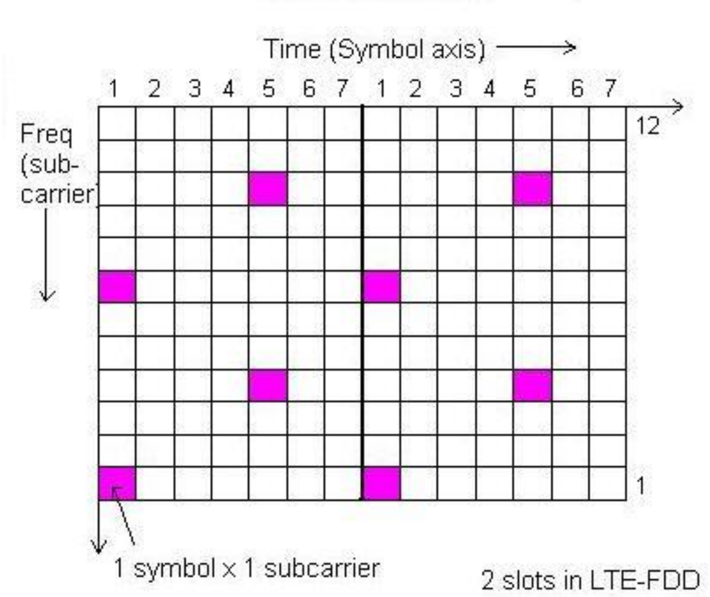
❑ Physical channel design of OFDM

➢ Peak downlink throughput of an LTE BS

There are 20MHz spectrum for an LTE BS. Assume that first 3 OFDM symbols in each subframes are reserved for control signals. Also, in each RB, 8 REs are carrying reference signals. The guarding band is 2 MHz. What is the peak throughput of the LTE system?

- Guarding band: a guard band is a narrow frequency range that separates two ranges of wider frequency. This ensures that simultaneously used communication channels do not experience interference, which would result in decreased quality for both transmissions.





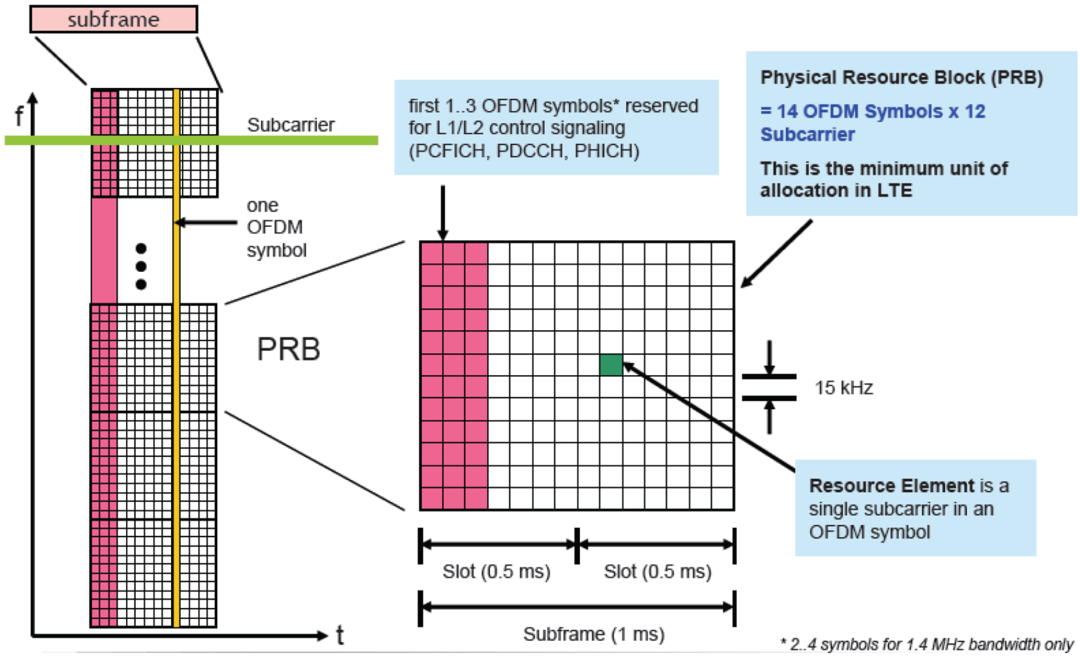
- Reference signals: when a UE tries to figure out the channel quality to its BS, it measures the power of the reference signals carried by different Res.

Key technologies in LTE

❑ Physical channel design of OFDM

➢ Peak downlink throughput of the LTE cell

There are 20MHz spectrum for the LTE system. Assume that first 3 OFDM symbols in each subframes are reserved for control signals. Also, in each RB, 8 REs are carrying reference signals. The guarding band is 2 MHz. What is the peak throughput of the LTE system?



PCFICH = Physical Control Format Indicator Channel, **PDCCH** = Physical Downlink Control Channel, **PHICH** = Physical HARQ Indicator Channel

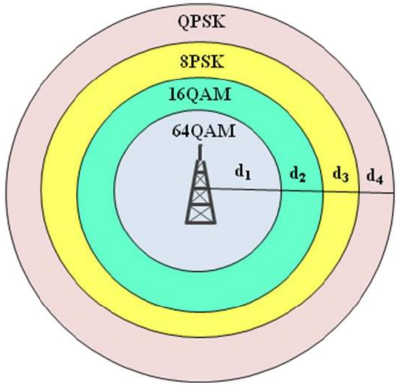
- # of RB in a subframe = (20-2)*1000/(15*12)=100
- Max # of bits taken by an RB = ((14-3)*12-8)*6=744
- Throughput=100*744 bits/ 1 ms= 74.4 Mbps

❑ Physical channel design of OFDM

➢ Average/Aggregate downlink throughput of the LTE cell

There are 20MHz spectrum for the LTE system. Assume that first 3 OFDM symbols in each subframes are reserved for control signals. Also, in each RB, 8 REs are carrying reference signals. The guarding band is 2 MHz.

If the UEs are uniformly distributed in the cell's coverage area and all the UEs equally share the bandwidth resources, what is the aggregate downlink throughput of the LTE cell? Assume that adaptive modulation is used as follows, where d4=R, d4-d3=d3-d2=d2-d1, and d1=0.4R (R is the radius of the cell).



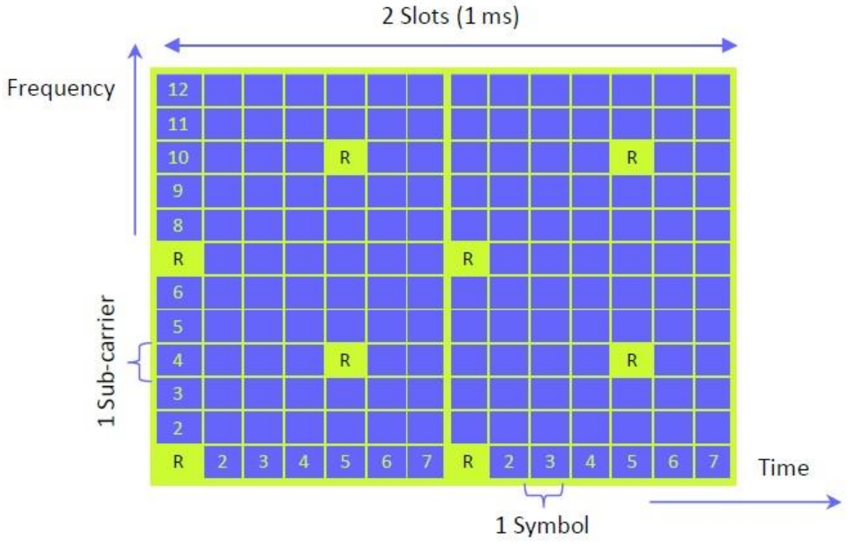
Key technologies in LTE

- Reference Signal Received Power (RSRP), Received Signal Strength Indication (RSSI), and Reference Signal Received Quality (RSRQ)

  - In cellular networks, when a UE moves from cell to cell and performs cell selection and handover, it has to measure the signal strength/quality of the neighbor cells.

  - Downlink cell reference signal.

    - ✓ UEs measure the received power of the reference signal
    - ✓ The reference signals are carried by multiple of specific REs.
    - ✓ Reference signals position in time domain is fixed whereas in frequency domain it depends on the Cell ID.



Key technologies in LTE

- Reference Signal Received Power (RSRP), Received Signal Strength Indication (RSSI), and Reference Signal Received Quality (RSRQ)

  - RSRP: average power (in watts) received from a single reference signal resource element.

$$RSRP = \frac{1}{K}\sum_{k=1}^{K} p_k$$

    where p_k is the received power of the kth reference signal resource element.

  - Knowledge of RSRP can be used to calculate downlink pathloss → distance between the UE and its associated cell.

  - RSRP does not indicate the received signal quality.
    - ✓ RSRP does a better job of measuring signal power from a specific sector/cell while potentially excluding noise and interference from other sectors/ cell s.

Key technologies in LTE

- Reference Signal Received Power (RSRP), Received Signal Strength Indication (RSSI), and Reference Signal Received Quality (RSRQ)

  - RSSI: the entire received power including the wanted power from the serving sector/cell as well as interferences and other sources of noise.

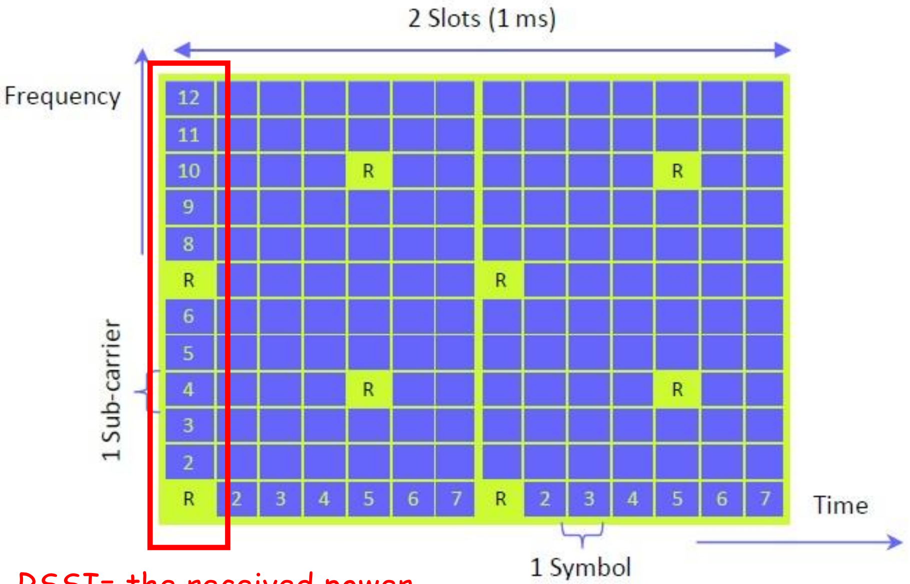
  - RSSI is measured only in OFDM symbol containing the RS.

  - RSRQ: indicate quality of the received signal.

$$RSRQ = \frac{RSRP}{(RSSI / N_{RB})}$$

where N_{RB} is the number of resource blocks.

  - Measuring RSRQ becomes particular important near the cell edge when decision need to be made to perform a handover to the next cell.



RSSI= the received power of all the subcarriers

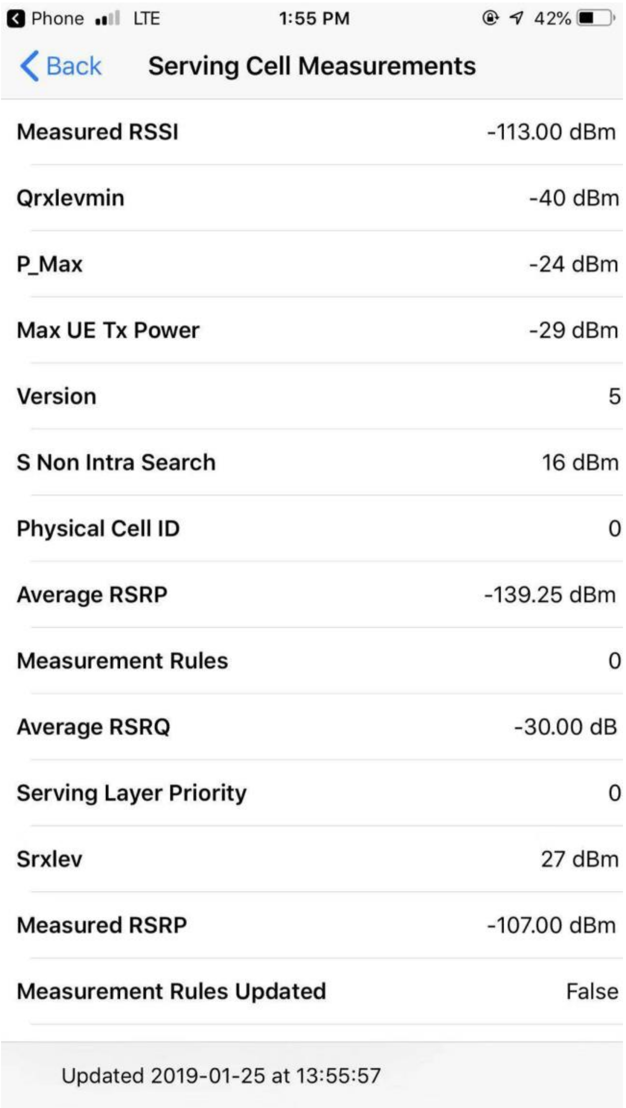
Key technologies in LTE

- Reference Signal Received Power (RSRP), Received Signal Strength Indication (RSSI), and Reference Signal Received Quality (RSRQ)

  - How to know the values of RSRP, RSSI, and RSRQ in your phone?

    - Field Test (dial *3001#12345#*)→ Serving Cell Measurements

Signal Quality	Technology	RSSI	SINR (dB)	RSRQ (dB)	RSRP (dBm)	EC/Io (dB)
		LTE and 3G	LTE only	LTE only	LTE only	HSPA+ and EVDO
	Excellent	> -65	> 12.5	> -5	> -84	> -2
	Good	-65 to -75	10 to 12.5	-6 to -10	-85 to -102	-2 to -5
	Fair	-75 to -85	7 to 10	-6 to -10	-103 to -111	-5 to -10
	Poor	< -85	< 7	< -11	< -112	< -10


Phone LTE 1:55 PM 42%
Back Serving Cell Measurements

Measured RSSI	-113.00 dBm
Qrxlevmin	-40 dBm
P_Max	-24 dBm
Max UE Tx Power	-29 dBm
Version	5
S Non Intra Search	16 dBm
Physical Cell ID	0
Average RSRP	-139.25 dBm
Measurement Rules	0
Average RSRQ	-30.00 dB
Serving Layer Priority	0
Srxlev	27 dBm
Measured RSRP	-107.00 dBm
Measurement Rules Updated	False

Updated 2019-01-25 at 13:55:57

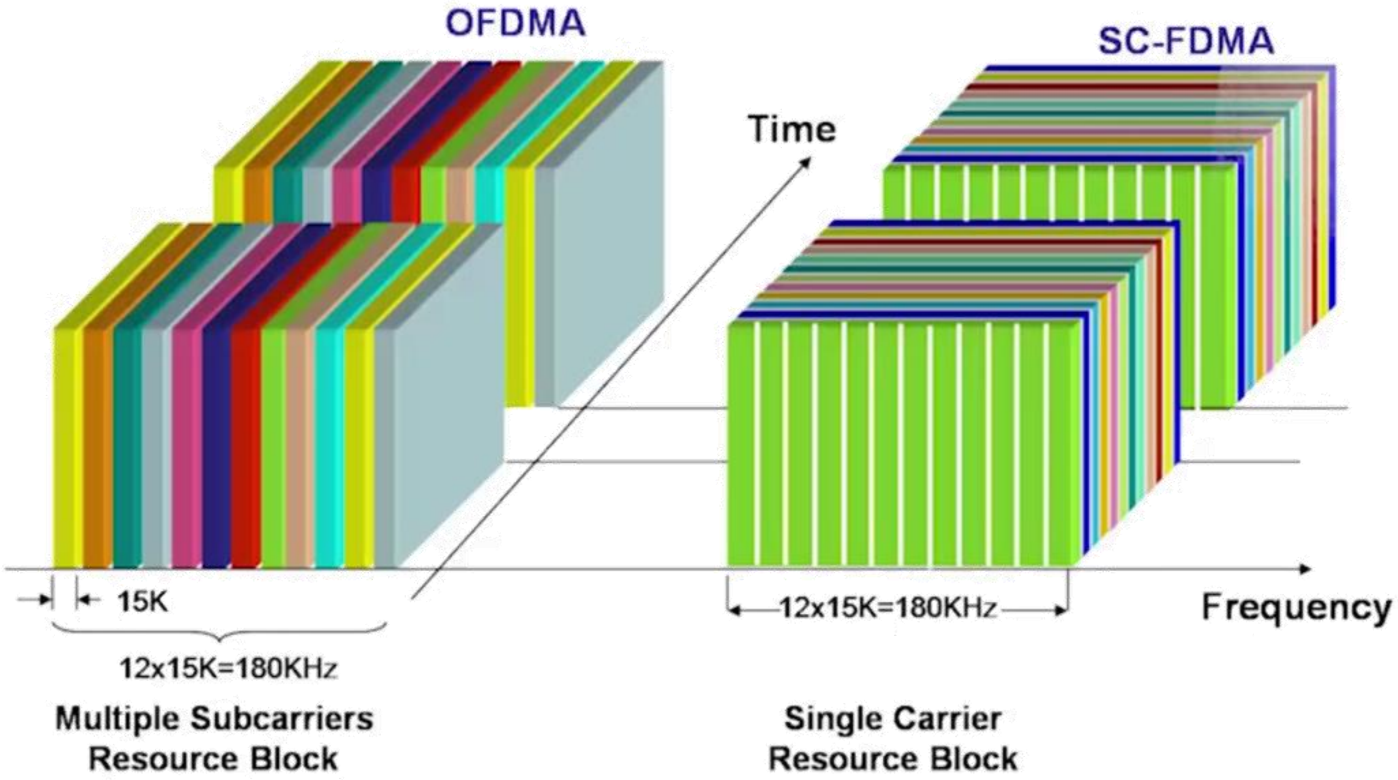
Key technologies in LTE

❑ SC-FDMA (Single carrier-FDMA)

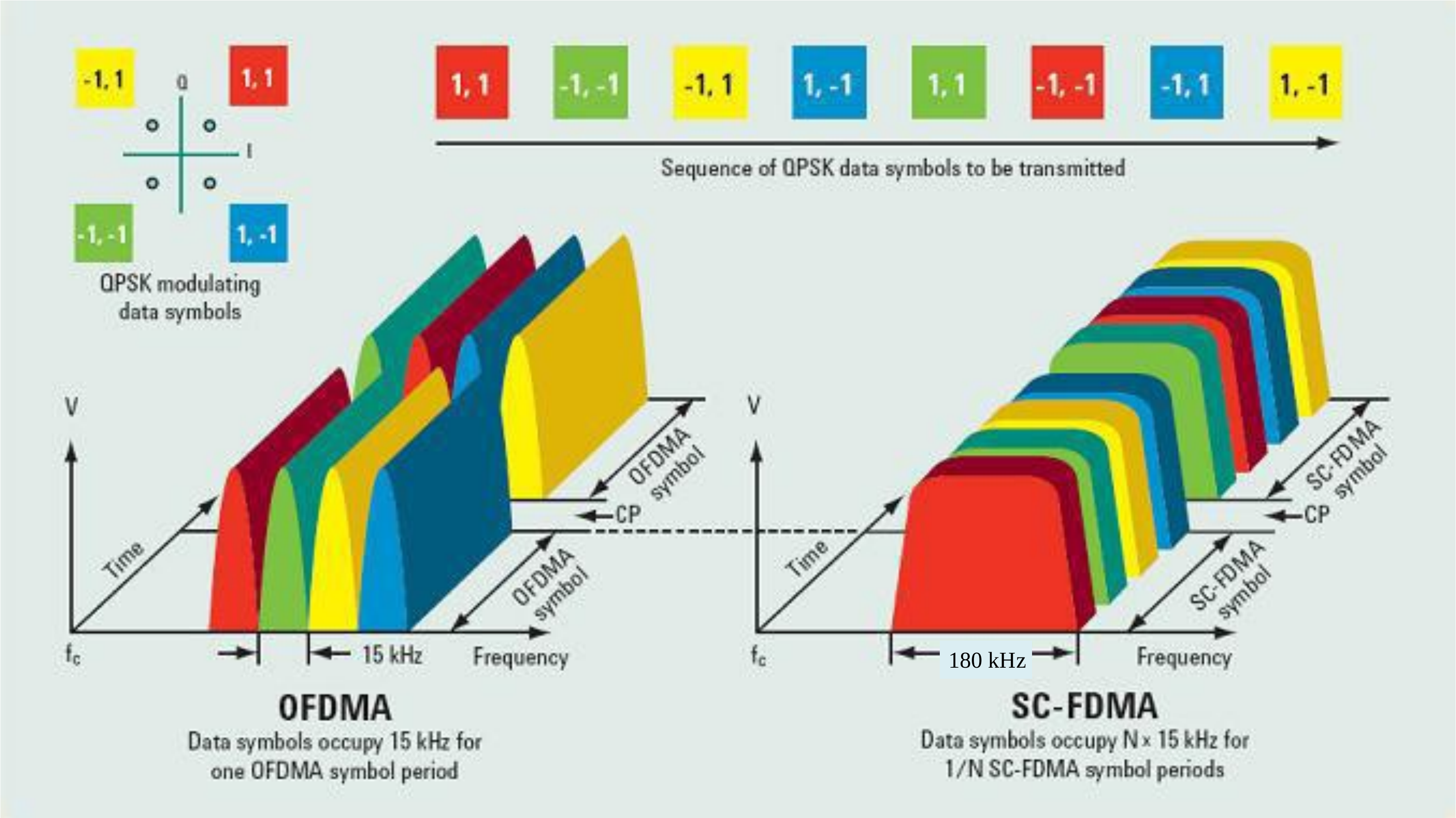
➢ SC-FDMA is used as the access technology in uplink communications (from UEs to BSs)

✓ In OFDMA, each sub-carrier only carries one data symbol. Each data symbol has a long symbol duration.

✓ In SC-FDMA, each sub-carrier contains information of all data symbols. Each data symbol has a short symbol duration.



❑ SC-FDMA

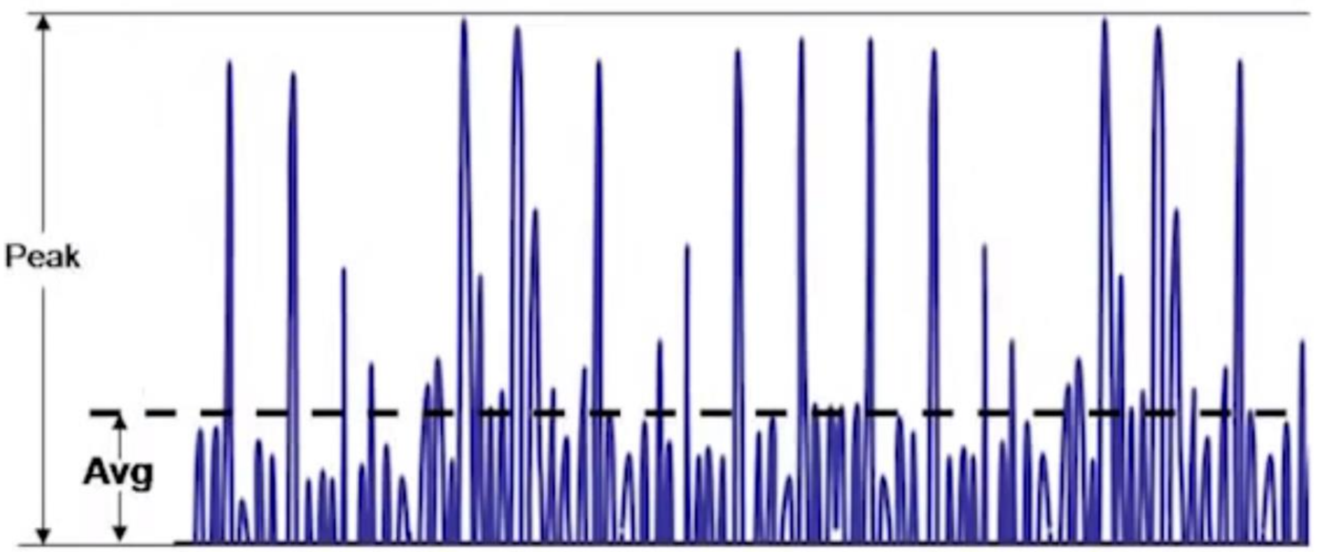

-1, 1
Q
1, 1
I
-1, -1
1, -1
QPSK modulating data symbols
1, 1
-1, -1
-1, 1
1, -1
1, 1
-1, -1
-1, 1
1, -1
Sequence of QPSK data symbols to be transmitted
V
Time
OFDMA symbol
CP
OFDMA symbol
f_c
15 kHz
Frequency
OFDMA
Data symbols occupy 15 kHz for one OFDMA symbol period
V
Time
SC-FDMA symbol
CP
SC-FDMA symbol
f_c
180 kHz
Frequency
SC-FDMA
Data symbols occupy N x 15 kHz for 1/N SC-FDMA symbol periods

❑ SC-FDMA (Single carrier-FDMA)

➢ Why use SC-FDMA in uplink communications?

✓ OFDMA suffers from high peak-to-average power ratio (PAPR) in the time domain.

  ○ PAPR of 10 dB means that for transmitting an average power of 0.2 W, the transmitter should be able to handle power peaks of 2.0 W (10 time higher).



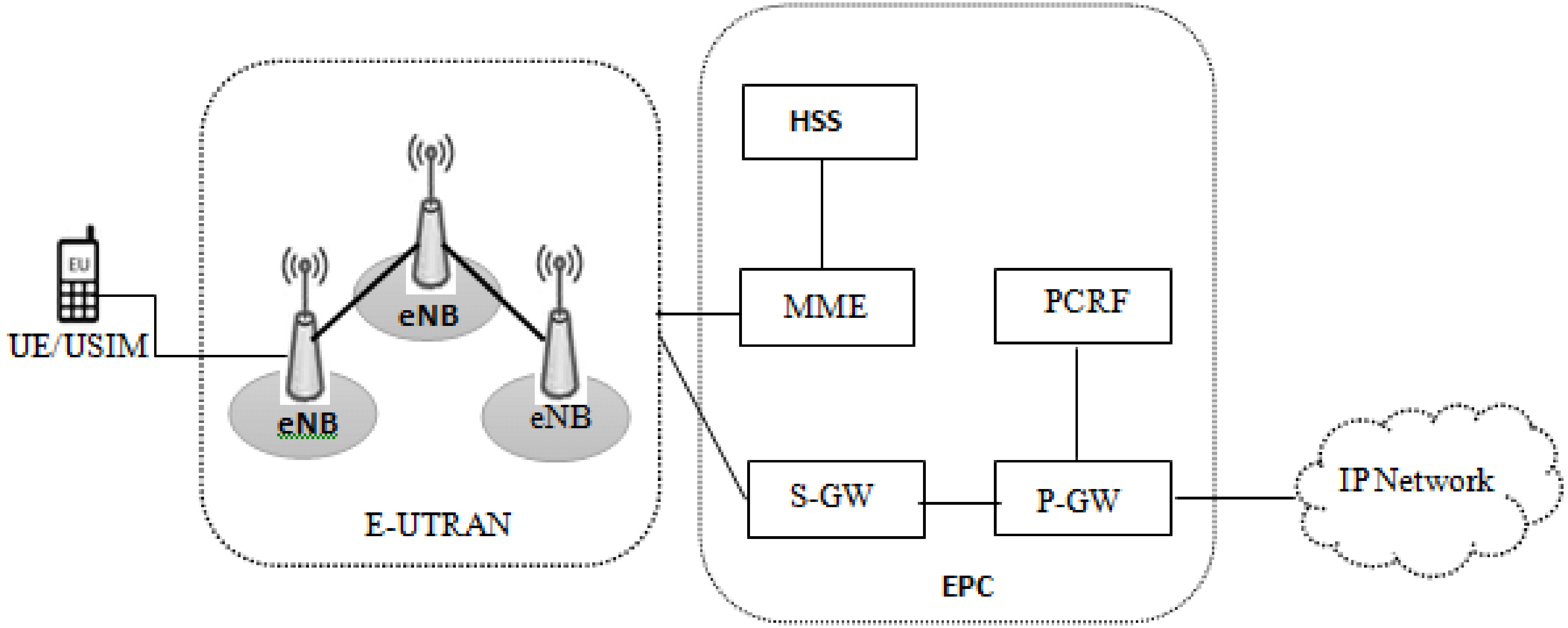
✓ High PARP incurs high energy consumption of the transmitter, and UEs are sensitive to energy consumption

✓ SC-FDMA incurs relative low PARP, thus saving the energy consumption of UE.

LTE Network Architecture

System overview

- ✓ The LTE network is comprised of the core network (Evolved Packet Core) and the access network (Evolved UMTS Terrestrial Radio Access Network)



System overview--EPC

- ✓ EPC is responsible for the overall control of the UE and establishment of the bearers. The main logic nodes of the EPC are:

  - PDN Gateway (P-GW)
    P-GW is responsible for IP address allocation for the UE, as well as QoS enforcement and flow-based charging according to rules from the PCRF. The P-GW is responsible for the filtering of downlink user IP packets into the different QoS-based bearers. The P-GW performs QoS enforcement for Guaranteed Bit Rate (GBR) bearers. It also serves as the mobility anchor for inter-working.

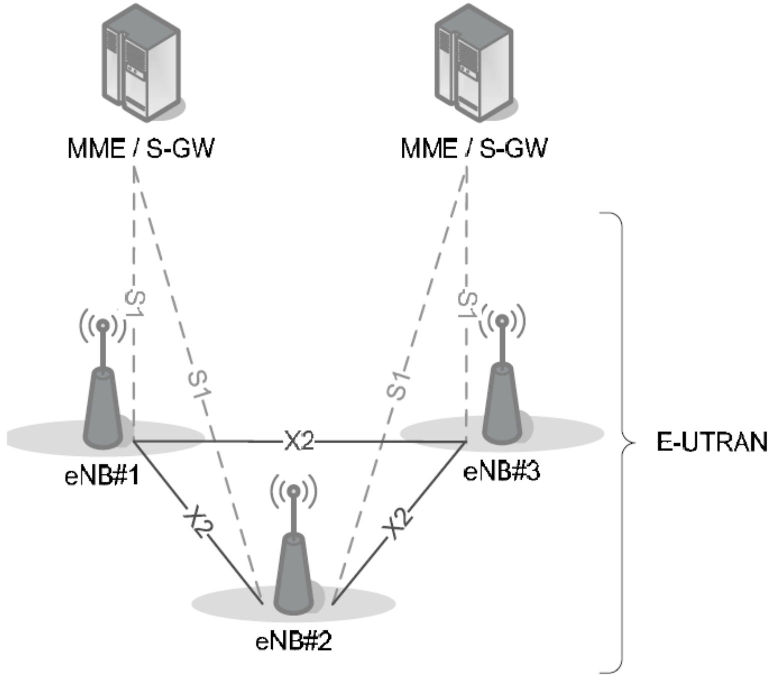
  - Serving Gateway (S-GW)
    All user IP packets are transferred through the S-GW, which serves as the local mobility anchor for the data bearers when the UE moves between BSs. It also provides temporarily buffers downlink data while the MME initiates paging of the UE to re-establish the bearers. In addition, the S-GW performs some administrative functions in the visited network, such as collecting information for charging (e.g. the volume of data sent to or received from the user) and legal interception. It also serves as the mobility anchor for inter-working with other 3GPP technologies

  - Mobility Management Entity (MME): session and location management, authentication, etc.

LTE Network Architecture

❑ System overview—Access network

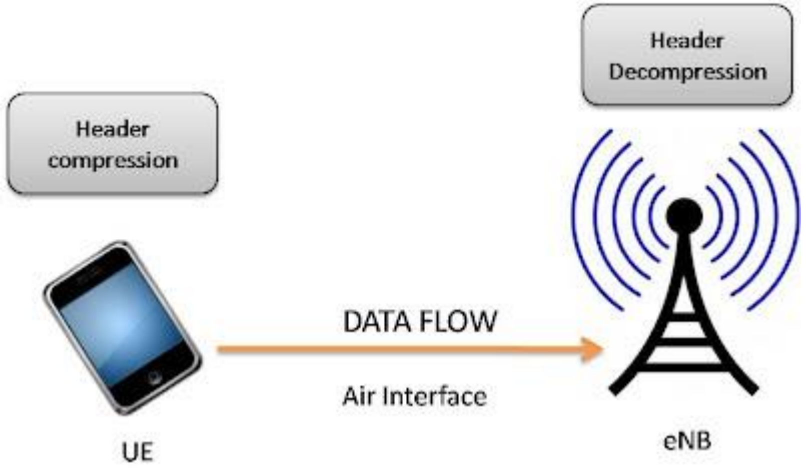
- ✓ The access network of LTE, E-UTRAN, simply consists of a network of eNodeBs.
- ✓ There is no centralized controller in E-UTRAN; hence the E-UTRAN architecture is said to be flat.
  - The network topology of eNodeBs is mesh.
  - Different MMEs/S-GWs can serve the same set of eNBs to achieve load sharing and resolve single failure problem.
  - Once a UE hands off, all information (the UE context together with any buffered data) related to the UE from one eNodeB to another.
- ✓ The functions of eNodeB
  - Provide Interfaces to UEs and EPC
  - Radio Resource Management
  - Header Compression/Decompression
  - Security
  - Positioning



System overview—Access network

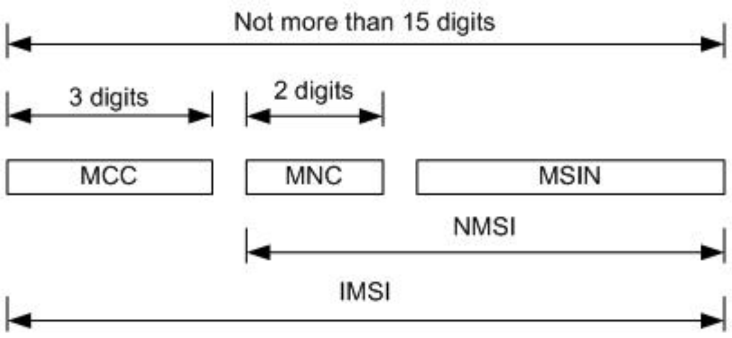
✓ Header Compression/Decompression in eNodeB

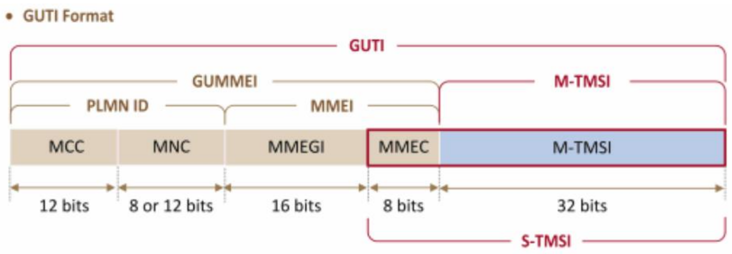
- For some applications (such as VoIP), the size of a packet header (IP/UDP/RTP) is usually larger than the size of packet payload/data itself.
  - Typically, for the transport of a VoIP packet which contains a payload of 32 bytes, the header added will be 60 bytes for the case of IPv6 and 40 bytes for the case of IPv4 – i.e. an overhead of 188% and 125% respectively.
- Transmitting a huge volume of header over the air (between a UE and its eNodeB) wastes the radio resources.
- Header compression is used to reduce size of the header during the transmission by allowing both the sender and the receiver to store the static parts of the header (e.g. the IP addresses of the sender/receiver), and to update these only when they change.



User Identifier in the network

- **Your phone number**
  - Mobile Station Integrated Services Digital Network Number (MSISDN)
  - Used to identify a subscriber when making a call or sending an SMS
- **You Mobile Identity**
  - International Mobile Equipment Identity (IMEI)
  - *#06#
- **International Mobile Subscriber Identifier (IMSI)**
  - Embedded in SIM card
  - Stored in subscription data of HSS (Home Subscriber System)
  - The mapping between MSISDN and IMSI is stored in HLR.
  - Transmitting ISMI through the air is not safe

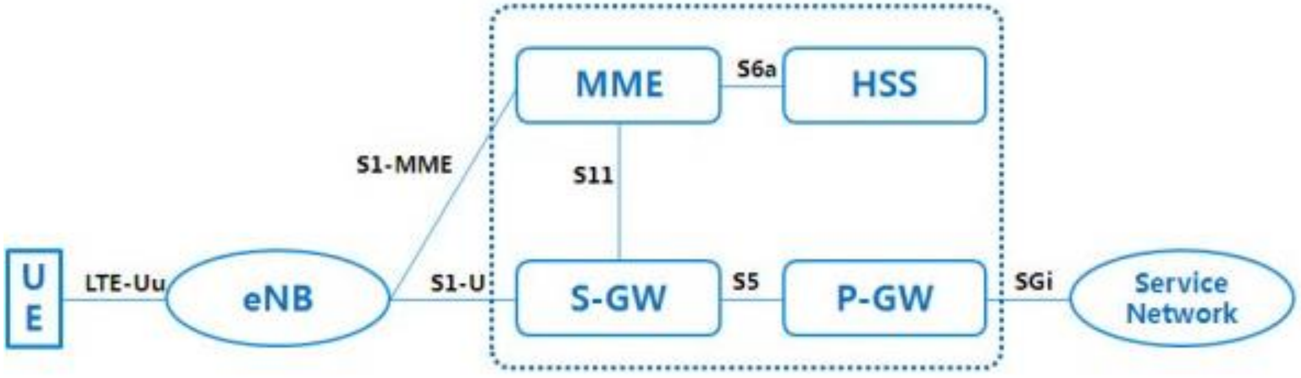




- **Global Unique Temporary ID (GUTI)**
  - Allocated by the MME when a UE attaches to the network.
  - May be different when the UE reattaches to the network (power-off and on) or updates its location.
  - The purpose of the GUTI is to provide an unambiguous identification of a UE that does not reveal the UE's IMSI.
- **Cell - Radio Network Temporary Identifier (C-RNTI)**
  - Unique identification used for identifying the RRC connection between a UE and its associated eNB.
  - The eNB assigns different C-RNTI values to different UEs.

❑ LTE Attach

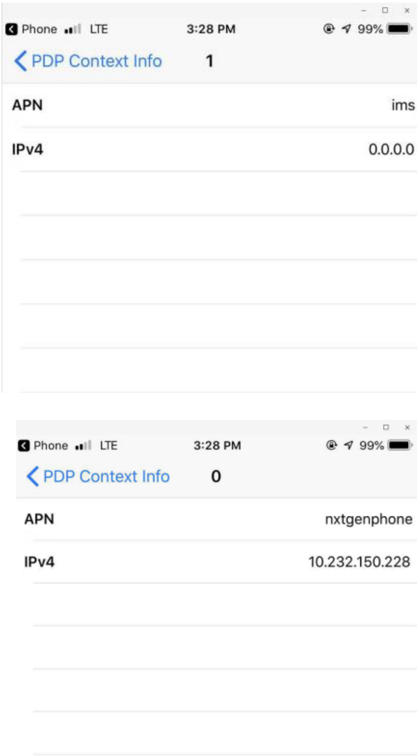
- ✓ Let the network know the UE (IMSI attach).
  - The UE sends the LTE attach request containing the IMSI of the UE to the MME via the eNB. The MME will conduct authentication with the help of HSS.
  - The MME will assign a GUTI to the UE.



- ✓ Initialize the data communications services by setting up a default EPS (Evolved Packet System) bearer between the UE and the P-GW.
  - Default EPS bearer will remain as long as the UE is attached.
  - Default EPS bearer is best effort service (Not guaranteed service).
  - Each default EPS bear comes with an IP address—an IP address will be assigned to the UE by the P-GW.
  - A UE may have multiple default EPS bears if the UE connects to multiple P-GWs.

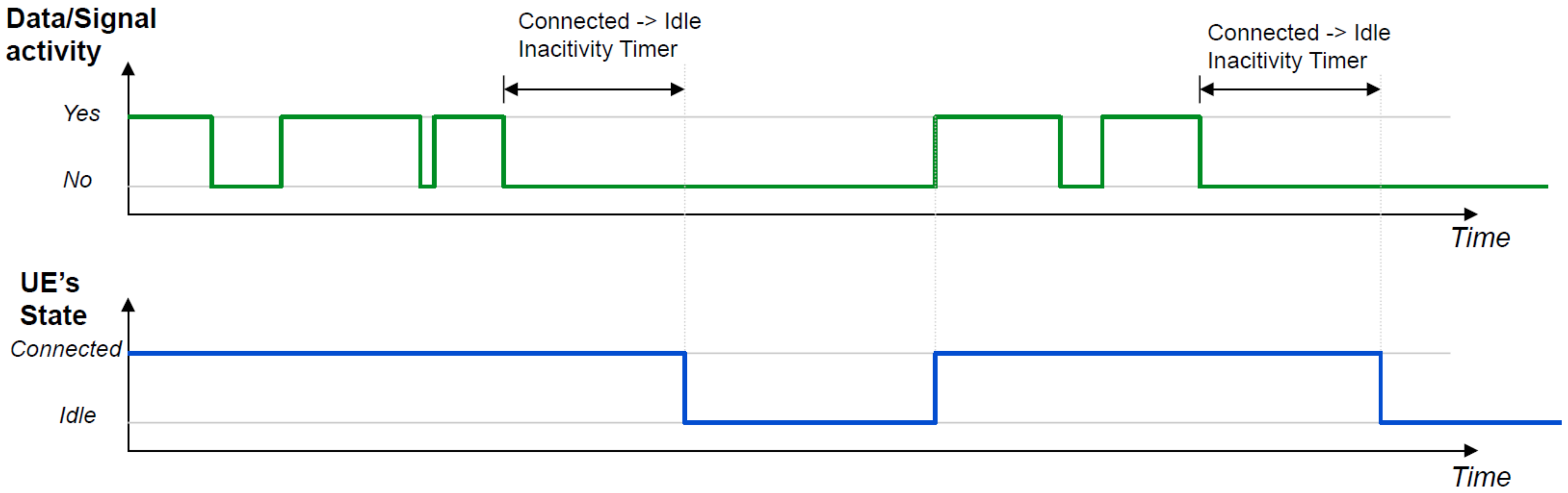
❑ LTE Attach

✓ A UE normally has two default EPS bearers w.r.t. two P-GWs
- IP Multimedia Subsystem (IMS) P-GW.
- Internet P-GW



❑ Different states of a UE in LTE

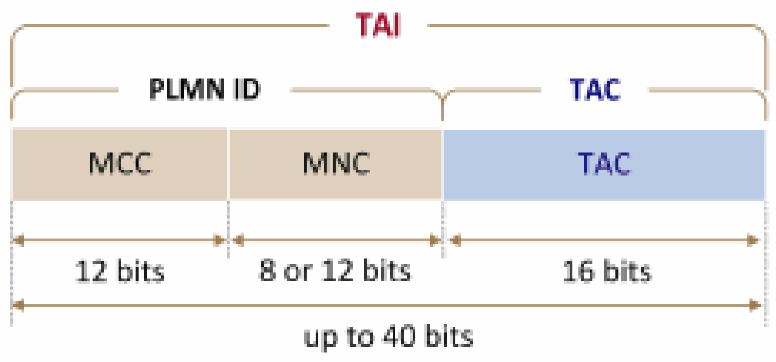
- **A UE in LTE can be in two states:**
  - **Connected Mode**: The UE is transmitting and receiving data from the network.
  - **Idle Mode**: The UE is only monitoring the paging and broadcast channel.
- **After the UE stops transmitting/receiving data/signal for a period of time, called inactivity period, the network moves the UE's state to idle-state**

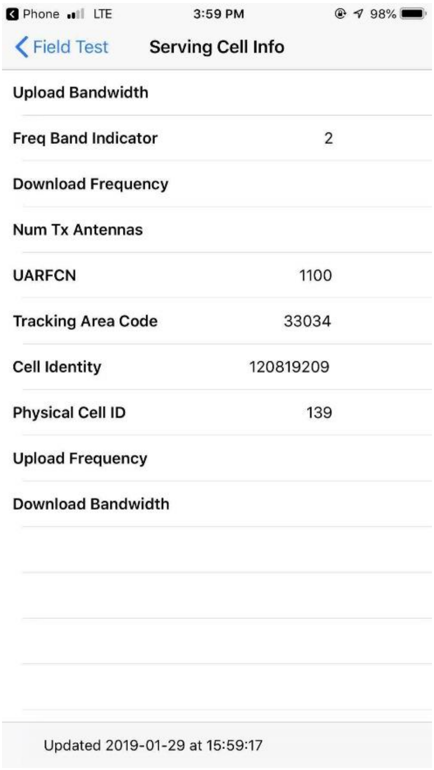


❑ Tracking Area

➢ The tracking area is similar to Location Area and Routing area, which is basically a geographical combination of several eNodeBs.

➢ Each tracking area is identified by a Tracking Area Identity (TAI).

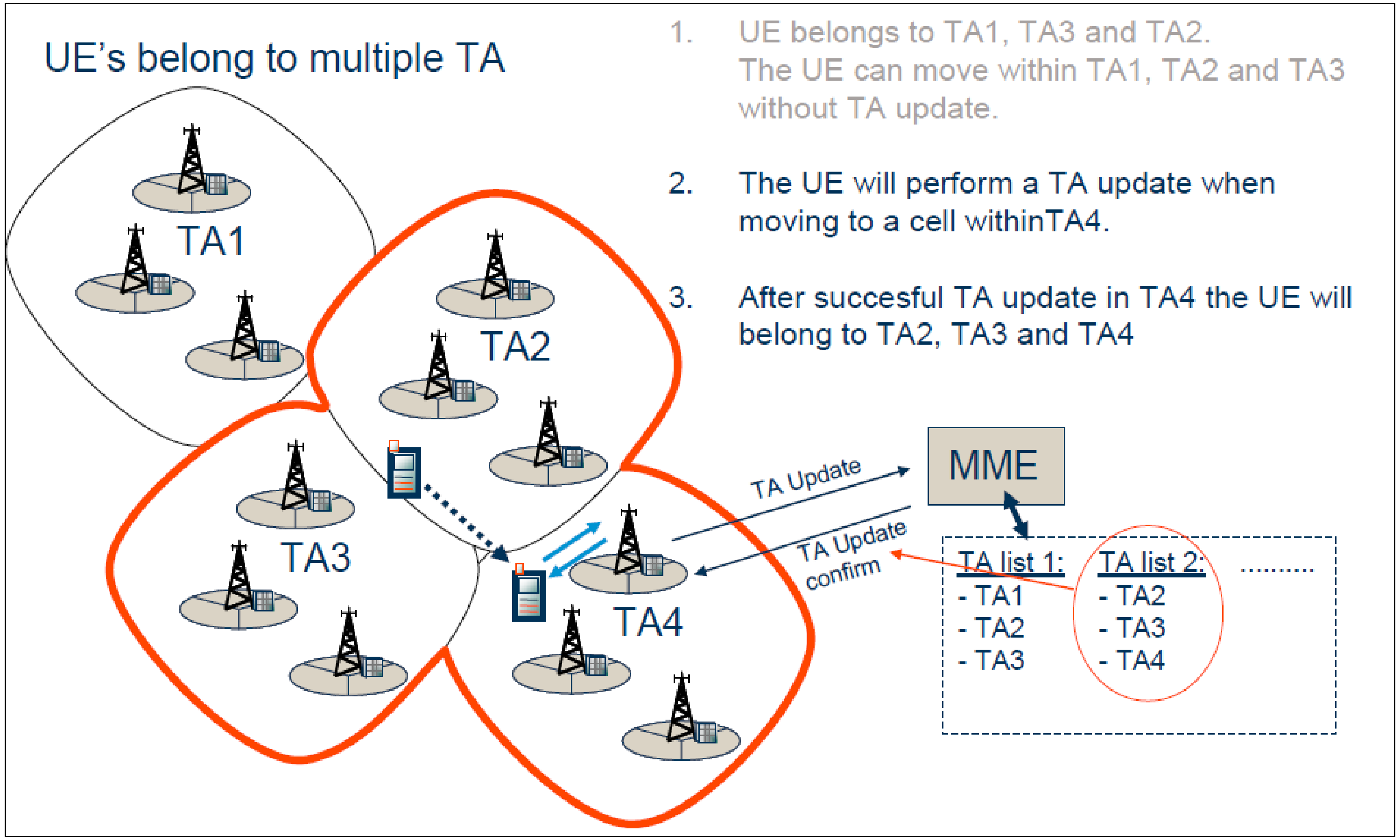




- ✓ Mobile Country Code (MCC)
- ✓ Mobile Network Code (MNC)
- ✓ Tracking Area Code (TAC)

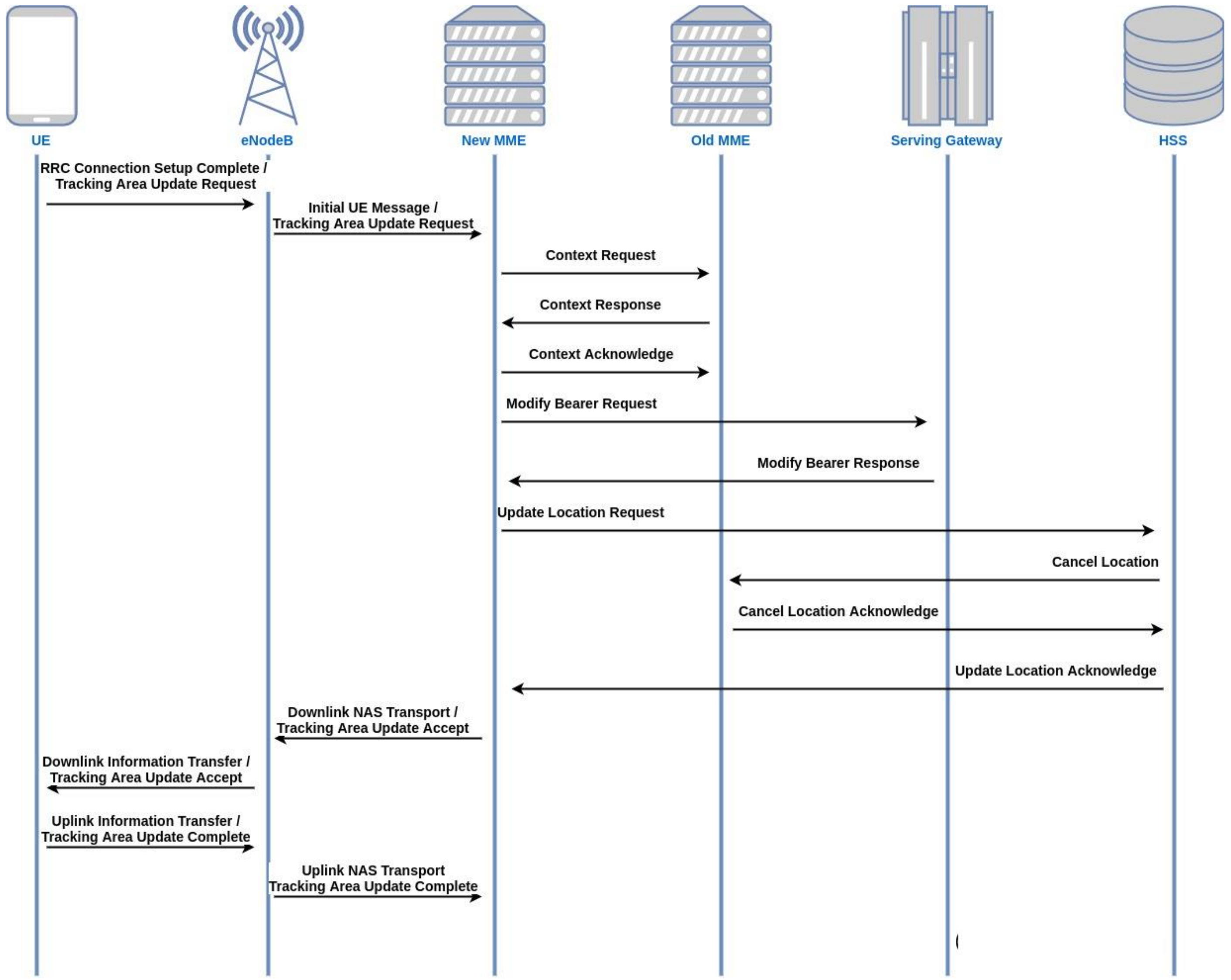
LTE Networks

❑ Tracking Area Update



- ✓ If the UE enters to a TA not in the TA list, the UE will trigger the TAU process.
- ✓ Also, if the periodic tracking area update timer (T3412) is expired, the UE will trigger the TAU process (to let the network know that it is alive).

Tracking Area Update

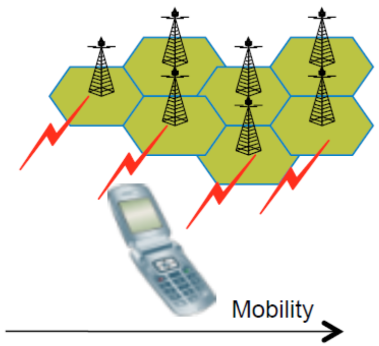


❑ Power management of UE

- ✓ High Power: "Connected Mode" when UE has both its transmitter and receiver always on.
- ✓ Low Power: "Idle Mode" when UE turns off it transmitter.

High Power Mode
Connected Mode

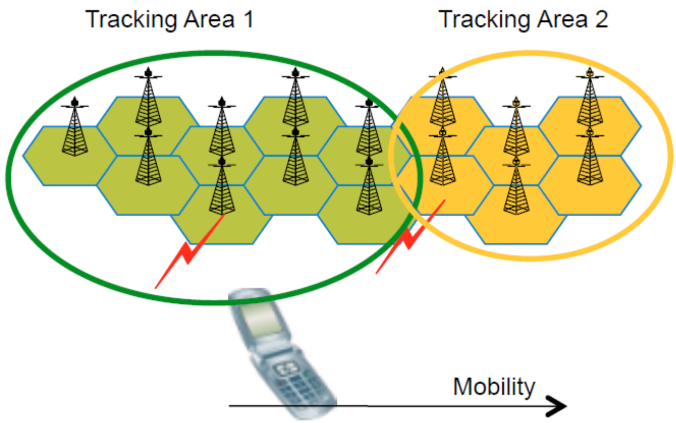
- ***Network controls UE's movement through handover.***
- ***Location of the UE is known to the network at granularity of a cell.***



- ***UE's radio is in ON state.***
- ***UE is constantly communicating with the network.***

Low Power Mode
Idle Mode

- ***Network does not control UE's movement. UE autonomously selects new cell as it moves.***
- ***Network only knows the location of the UE to the granularity of a tracking-area.***



- ***UE's radio is in low-power state. UE's transmitter is off.***
- ***UE only listens periodically to control channel. If UE enters a new location area, based on hearing information from base-station, the UE informs the network of the new tracking area it has entered.***

❑ Handover in LTE

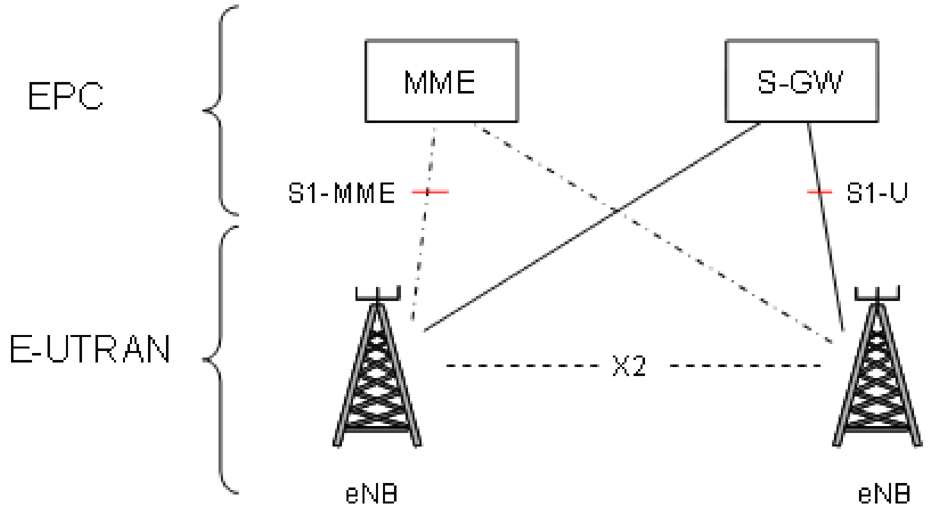
- **All handovers in LTE are prepared handovers**
  - Resources are prepared in the target eNB, before the UE connects to the target eNB
- **All handovers in LTE are UE assisted network controlled**
  - The UE is asked to make measurements of neighbouring cells by the source eNB and report back to the source eNB.
  - The source eNB decides as to which target eNB the UE should be handed over to and directs the UE to that particular target eNB.

LTE Networks

❑ Handover in LTE

➢ X2 handover

✓ X2 interface is the connection between two neighbor eNBs.
✓ X2 handover occurs when the source eNB and target eNB are within the same MME, and X2 interface is defined between the two eNBs.

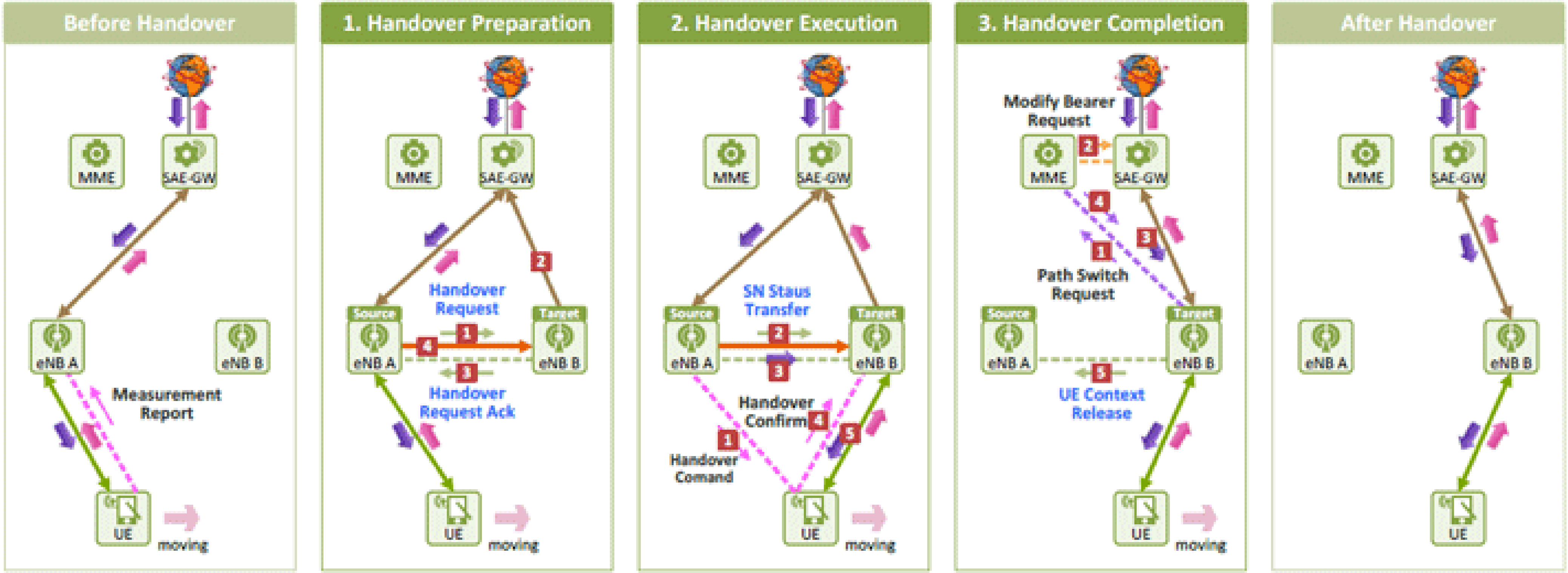


➢ S1 handover

✓ S1 interface is the connection between an eNB and MME/S-GW
✓ S1 handover occurs when the source eNB and target eNB are not connected with same MME or the X2 interface is not defined between the two eNBs or when X2 procedure fails (due to unreachability/Error response etc).

LTE Networks

- X2 handover



Before Handover

- Serving eNB of UE: eNB A
- UE performs neighbor cell measurement.
- UE sends a **Measurement Report** message to eNB A (periodically or if triggered by measurement events).

1. Handover Preparation

- eNB A (SeNB) decides to perform X2 HO to eNB B (TeNB).
- SeNB requests HO to TeNB (1), and TeNB notifies SeNB of successful HO preparation (3).
- TeNB makes ready to send UL packets (via UL S1 bearer, 2) and receive DL packets (via DL X2 bearer, 4).
- A Direct tunnel for DL packet forwarding is established between SeNB and TeNB (4).

2. Handover Execution

- SeNB commands UE to perform HO (1), transfers the DL/UL packet status to TeNB (2) and forwards DL packets to TeNB via the X2 bearer (3).
- UE detaches from SeNB and accesses TeNB (4).
- TeNB buffers the DL packets and forwards them to UE after UE has accessed (5).

3. Handover Completion

- TeNB informs MME that UE has changed its serving cell (1).
- MME requests modification of the S1 bearer to SAE-GW (2), and SAE-GW switches the DL path to TeNB (3).
- MME notifies TeNB of the path switch (4).
- TeNB requests SeNB to release the resources (5).

After Handover

- Serving eNB of UE: eNB B

DRB (Data Radio Bearer) | S1 Bearer (GTP Tunnel) | X2 Bearer (GTP Tunnel) | S11 (GTP-C) Signaling | UL Traffic
Signaling in Radio | S1 Signaling | X2 Signaling | DL Traffic

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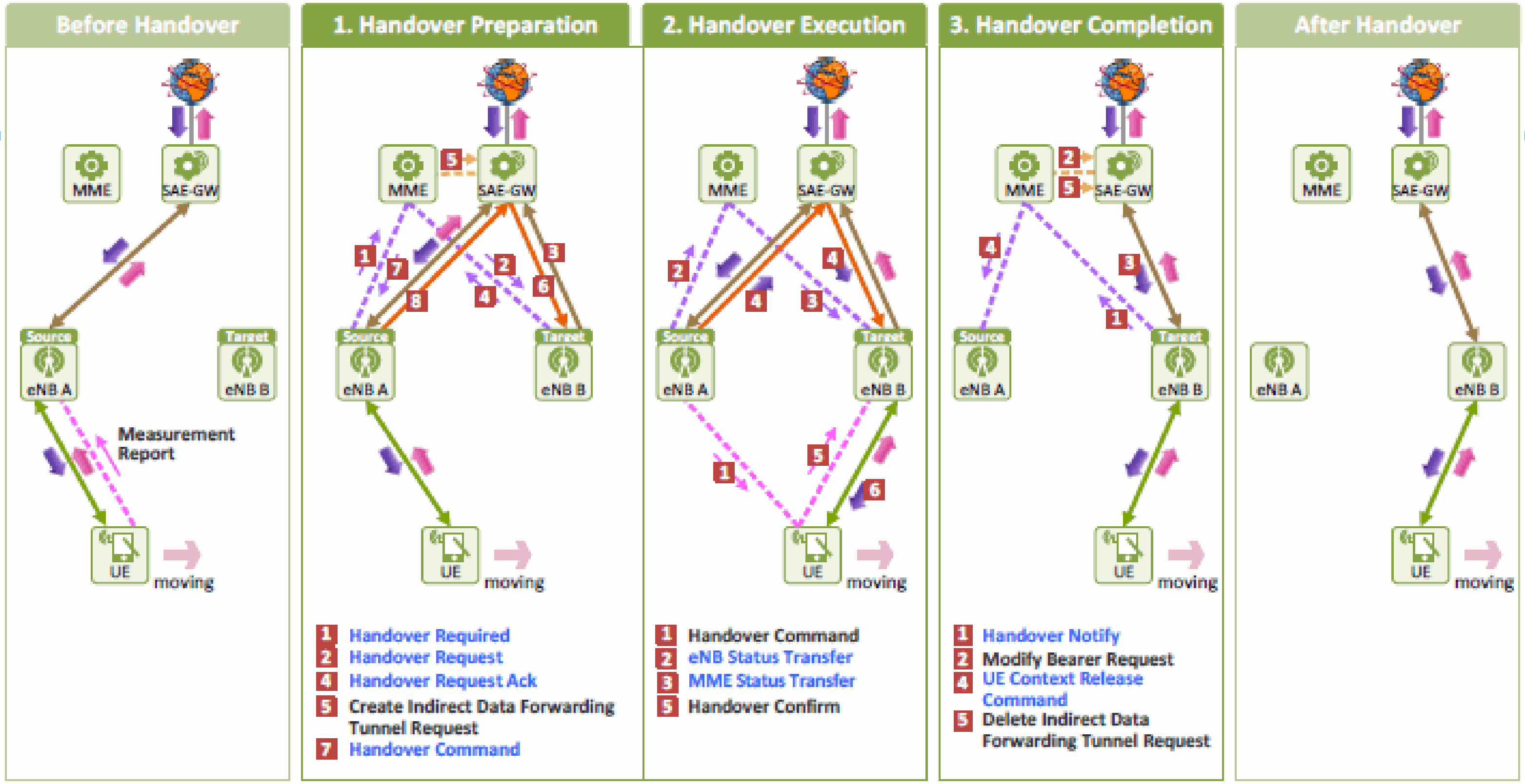
LTE Networks

- S1 handover



Before Handover

- Serving eNB of UE: eNB A
- UE performs neighbor cell measurement.
- UE sends a **Measurement Report** message to eNB A (periodically or if triggered by measurement events).

1. Handover Preparation

- eNB A (SeNB) decides to perform S1 HO.
- SeNB requests HO to MME (1), and MME requests HO to TeNB (2).
- TeNB makes ready to send/receive UL/DL packets (via UL/DL S1 Bearer) with SAE-GW (3). Then, it prepares to receive DL packets forwarded from SeNB (via indirect tunnel) and notifies MME of the indirect tunnel info (4).
- MME informs SAE-GW of the indirect tunnel info (5) and SAE-GW establishes an indirect tunnel with TeNB (6).
- MME sends SeNB the info necessary to establish an indirect tunnel to SAE-GW and the info necessary when UE accesses TeNB (7).
- SeNB establishes an indirect tunnel to SAE-GW (8).

2. Handover Execution

- SeNB commands UE to perform HO (1).
- SeNB sends the UL/DL packet status (SN) to TeNB via MME (2,3).
- SeNB forwards DL packets to TeNB via the indirect tunnels composed of (SeNB – SAE-GW) and (SAE-GW – TeNB) paths (4), and TeNB buffers the DL packets.
- UE detaches from SeNB and accesses TeNB (5).
- TeNB forwards the DL packets which have been buffered to UE after UE has accessed (6) .

3. Handover Completion

- TeNB informs MME that UE has changed its serving cell (1).
- MME requests modification of the S1 bearer to SAE-GW (2), and SAE-GW switches the DL path to TeNB (3).
- MME requests SeNB to release the UE Context (4), and SeNB releases it.
- MME requests SAE-GW to release the resources used for indirect forwarding (5), and SAE-GW releases it.

After Handover

- Serving eNB of UE: eNB B

Data Radio Bearer (DRB)
S1 Bearer (GTP-U Tunnel)
S1 Bearer for Indirect Forwarding (GTP-U Tunnel)
Signaling over Radio
S1 Signaling
S11 Signaling (GTP-C Tunnel)
UL Traffic
DL Traffic